Detecting Nuclear Materials from Cosmic-Ray Muon Scattering

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One of the greatest threats to our nation is the possibility of terrorists detonating a nuclear device in a city or port. While obtaining such a device or the materials with which to make one is difficult, the task of smuggling such into the country seems much less so. Materials can be brought in by ship or truck in a cargo container or in the trunk of a car crossing the border. The magnitude of the threat justifies the effort required to attempt to detect nuclear materials that may arrive by any of these means.

Existing technologies include passive radiation detectors and active interrogation methods. The latter involves subjecting a vehicle or container to radiation (such as X-rays) and looking for evidence of induced fission. Both have the advantage of being selective to fissile materials. Both have the disadvantage of being completely stopped by encasing such materials with lead or other shielding. Active interrogation is limited by the requirement to minimize health risks, and by the regulatory burden of deploying radiation sources.

A promising alternative comes from a natural, ever-present shower of muons that come from cosmic rays striking the atmosphere. Muons are heavier cousins of electrons, and have an electric charge. They arrive at the ground travelling nearly the speed of light, and easily penetrate feet of lead and hundreds of yards of rock. Yet their charge allows them to be easily detected. They will be deflected by the electric charge of atoms in any matter they pass through, to an extent that increases with atomic number (Z) and density. It is this fact that allows the measurement of muon scattering to distinguish between dense, high-Z materials, such as uranium, and less dense, lower-Z materials, such as iron or water.

Traditional forms of radiography produce images in which the contrast is provided by different radiation intensities being measured at different places in the image. On the one hand, the flux of cosmic-ray muons is too low to provide such a contrast in a short period of time. On the other hand, the muon's charge allows information to be extracted from every individual muon detected. It is this approach that allows us to make decisions on the presence of high-Z material in a vehicle or container in roughly a minute.

Pairs of detectors placed around a vehicle or container allow each muon to be detected in two places before entering the test volume and in two places after leaving. The low flux and the near-light speed of the muons allows entry and exit detection events to be associated with the same muon. Information extraction techniques begin by measuring the total angular change of each muon, and by tracking the entry and exit paths back into the test volume to determine where the angle change likely occurred. The paths will not in general exactly cross, as muons scatter multiple times while passing through matter. There will be a single point that is closest to both paths; this point of closest approach (POCA) is the best point estimate for where each muon scattered.

A simple form of image reconstruction consists of computing a three-dimensional histogram of scattering angles, assigned to bins (voxels) according to POCA locations. However, this method is not robust to medium-Z clutter in the cargo; for example, a layer of iron in the bottom of a cargo container will cause POCA locations to have a downward bias. To overcome this, we incorporate other information available from each muon to come up with a more robust way to assign muon scattering to voxels. A foundation of several approaches is to measure distances from a muon's POCA with a "physics-based" distance function. This function adjusts the usual distance according to how far apart the entry and exit paths are at their closest: when these are far apart, the POCA location has greater uncertainty, so the distance from points in the vehicle or container to the POCA should be less than when the paths nearly cross. Furthermore, the distance function orients this uncertainty correctly, by using a coordinate basis whose orientation relative to the POCA is determined by the geometry of the entry and exit paths.

The overall approach to detecting high-Z material in a vehicle or container has two steps: First, identify locations that are most likely to have high-Z material. Second, use a machine-learning classifier to test the candidate locations.

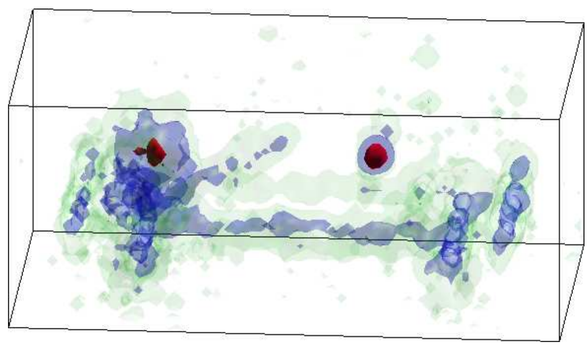
We have used two approaches to identify candidate locations. One is to apply a clustering routine for the POCAs corresponding to the most-scattered muons. The centroids of the clusters are the candidate locations. Both the clustering routine and the determination of the centroids use the physics-based distance function discussed above.

The second approach is to construct a potential function that measures, in some sense, the likelihood of a location being associated with the scattering of muons. It is then a matter of calculus to determine local maxima for this function, which are the candidate locations. The potential function also makes use of the physics-based distance function.

The second step uses machine learning algorithms whereby a computer teaches itself how to distinguish locations of high-Z material from other locations. The computer is given many samples of muon-scattering data corresponding to many locations with high-Z material and to many without, and is told which are which. The algorithm trains itself to distinguish the difference between the two directly from the data, and can then predict whether data for a new location has high-Z material.

The data is processed for use by the machine-learning algorithm by computing scattering statistics for each voxel in a vehicle or container. A muon's scattering is assigned to voxels depending on how far a voxel is from that muon's POCA, measured by the physics-based distance function. This results in the quantification and orientation of the uncertainty for each POCA being incorporated into the voxel statistics.

In tests of the combined, two-step procedure using data from computer simulations, cargo containers with high-Z material were detected 97% of the time after 60 seconds of muon exposure, while containers without high-Z material were correctly identified as such 98% of the time after the same duration of muon exposure. Other tests suggest that a majority of cars and trucks crossing a border could be cleared as harmless in as little as 20 seconds of muon exposure. Increasing the duration of exposure results in greater accuracy for the small fraction of border traffic with heavy, complicated cargo.



An image of muon scattering. Analyzing muon scattering data allows high-atomic number materials to be distuingished from other materials. The data are from a computer simulation of an automobile with two 20-kg uranium spheres. These show up in red, and are clearly distinguishable from the metal of the automobile.

Acknowledgements

Los Alamos Report LA-UR-04-5766. Funded by the Department of Energy under contracts W-7405-ENG-36 and the DOE Office of Science's Advanced Scientific Computing Research (ASCR) program in Applied Mathematical Sciences. Funded by the Department of Energy under contracts W-7405-ENG-36 and the Los Alamos Laboratory Directed Research and Development (LDRD) Program.

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